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"A Search for Hot, Diffuse Gas in Superclusters"

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The HEAO1 A2 full sky, 2-10 keV X-ray map was searched for diffuse emission correlated with the plane of the local supercluster of galaxies and a positive correlation was found at the 99% confidence level. The most obvious interpretation is that the local supercluster contains a substantial amount of hot ( $10^8$  °K), diffuse gas, i.e. ionized hydrogen, with a density on the order of  $2 - 3 \times 10^{-6}$  ions per cubic centimeter. This density is about an order of magnitude larger than the average baryon density of the universe and is consistent with a supercluster collapse factor of 10. The implied total mass is of the order of  $10^{16}$  times the mass of the sun and would constitute a large fraction of the baryonic matter in the local universe. This result supports current thinking that most of the ordinary matter in the universe is in the form of ionized hydrogen; however, the high temperature implied by the X-ray emission is at the top of the range predicted by most theories. The presence of a large amount of hot gas would leave its imprint on the Cosmic Microwave Background (CMB) via the Sunyaev-Zel'dovich (SZ) effect. A marginal decrement ( $-17 \mu\text{K}$ ) was found in the COBE 4-year 53 GHz CMB map coincident with the plane of the local supercluster. Although the detection is only  $1\sigma$ , the level is consistent with the SZ effect predicted from the hot gas. If these results are confirmed by future observations they will have important implications for the formation of large-scale structure in the universe.

Three other projects related directly to the HEAO 1 map or the X-ray background in general benefited from this NASA grant. They are: (1) "Correlations between the Cosmic X-ray and Microwave Backgrounds: Constraints on a Cosmological Constant"; (2) "Cross-correlation of the X-ray Background with Radio Sources: Constraining the Large-Scale Structure of the X-ray Background"; and (3) "Radio and X-ray Emission Mechanisms in Advection Dominated Accretion



Flows". All of these studies grew out of the research funded by the present NASA grant, and I have acknowledged the grant in four publications relating to these topics.

Several Haverford undergraduates have participated in this project. Lynne Raschke (four weeks during the summer of 1995) and Michael Lerner (ten weeks during the summer of 1996) were supported by this grant. Edward Stamas '96 completed a physics senior thesis on a model of the fluctuations in the cosmic microwave background due to the Sunyaev-Zel'dovich effect (with the above amplitude) in superclusters. Stamas is currently a data analyst employed by the Center for Astrophysics at Harvard.

The results of the "supercluster" project have been presented as colloquiums at the National Radio Astronomy Observatory (May, 1996) and at Rutgers University (December, 1996), and at the American Astronomical Society meeting in Madison, WI (June, 1996). A detailed description of results appear in a paper which is currently under review by the *Astrophysical Journal*. This manuscript and the four papers mentioned above are included with this report.

#### Publications:

1. "Evidence for Hot, Diffuse Gas in the Local Supercluster", under review by the *Astrophysical Journal* (1998).
2. "Cross-correlation of the 2-10 keV X-ray Background with Radio Sources: Constraining the Large-Scale Structure of the X-ray Background", *Astrophysical Journal*, volume 499, 533 (1998).
3. "Correlations between the Cosmic X-ray and Microwave Backgrounds: Constraints on a Cosmological Constant" (with R. Crittenden and N. Turok), *New Astronomy*, volume 3, 275 (1998).
4. "Radio/X-ray Luminosity Relation for Advection-Dominated Accretion: Implications for Emission-Line Galaxies and the X-ray Background" (with I. Yi), *Astrophysical Journal*, volume 499, 198 (1998).
5. "On Radio and X-ray Emission Mechanisms in Nearby, X-ray Bright Galactic Nuclei" (with I. Yi), *Astrophysical Journal*, volume 515, in press (1998).



FINAL EQUIPMENT AND PROPERTY INVENTORY REPORT

none

INVENTIONS DISCLOSURE REPORT

none



# Evidence for Hot, Diffuse Gas in the Local Supercluster

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## ABSTRACT

The HEAO1 A2 full sky, 2 – 10 keV X-ray map was searched for emission correlated with the plane of the local supercluster of galaxies. After removing strong point and moderately extended sources (e.g. the core of the Virgo cluster), there remained a statistically significant component of “diffuse” X-rays in the plane of the supercluster. Fitting this diffuse component with a simple “pillbox” model of the local supercluster implies a volume X-ray emissivity of  $\epsilon_x = 3.0 \pm 0.3 \times 10^{39} (R_{SC}/20 \text{ Mpc})^{-1} \text{ erg s}^{-1} \text{ Mpc}^{-3}$  where  $R_{SC}$  is the radius of the supercluster and the error is photon counting noise only. If one considers fluctuations in the X-ray background as an additional component of noise then the significance of the detection is reduced to 2 to  $3\sigma$ . This is consistent with fits of the model to data sets obtained by rotating the original data. The distribution of these rotated fits indicates that the detection is significant at the 99% confidence level. If the source of the X-ray emission is Bremsstrahlung from a uniformly distributed plasma with temperature  $T_e$  then the implied electron number density is  $N_e = 2.5 \times 10^{-6} (R_{SC}/20 \text{ Mpc})^{-\frac{1}{2}} (kT_e/10 \text{ keV})^{-\frac{1}{4}} \text{ cm}^{-3}$ . This value is about an order of magnitude larger than the average baryon number density implied by nucleosynthesis and is consistent with a collapse factor of 10. A search for similar structure in the COBE 53 GHz microwave background map yielded a marginal detection with an amplitude of  $\sim -17 \pm 5 \mu\text{K}$  (statistical error only) which is consistent with the Sunyaev-Zel’dovich (SZ) effect expected from 10 keV gas. This latter value is comparable to the amplitude of intrinsic large-scale fluctuations in the microwave background and should be considered to be a  $1\sigma$  result at best.

*Subject headings:* diffuse radiation – large-scale structure of the universe – X-rays: galaxies – X-rays: general

## 1. Introduction

The largest known structures in the clustering hierarchy of galaxies are flattened distributions known as “superclusters” (SCs). The local supercluster (LSC), the supercluster

of which the Galaxy is a member, was initially discussed by de Vaucouleurs (1953). Since then catalogues containing hundreds of SCs have been compiled (Bahcall & Soneira 1984; Batuski & Burns 1985; Einasto et al. 1997). Although it seems likely that many, if not most, SCs are gravitationally bound structures, they are far from virialized. Never-the-less, Small et al. (1998) have recently used virial type arguments to place a lower limit on the mass of the Corona Borealis SC. The fact that SCs are only marginally over-dense, i.e.  $\delta\rho/\rho \sim 10$ , further complicates studies of their structures. While the study of SCs is in its infancy, these objects promise to provide important information about the formation of large-scale structure in the Universe.

If little is known about the dynamics of SCs, even less is known about the intra-supercluster (ISC) medium. Assuming SCs have baryon-to-light ratios comparable to rich clusters of galaxies, then one expects a substantial amount of ISC gas. Furthermore, the virial temperatures of SCs are  $\sim 10^8$  K so it would not be surprising to find “hard” ( $> 1$  keV) X-ray emission from the ISC medium as is the case for the intergalactic medium in rich clusters of galaxies. Most models of structure formation predict the presence of a hot ISC, whether it is primordial, created from winds from an early population of stars, or tidally stripped from merging structures (Molnar & Birkinshaw 1998 and references cited therein). Estimated temperatures range from  $10^6$  K to  $10^8$  K (Klypin & Kates 1991; Rephaeli & Persic 1992; Metzler & Evrard 1994; Anninos & Norman 1996). It is straightforward to show that the cooling time for such gas at the expected densities ( $< 10^{-3}$  cm $^{-3}$ ) is much longer than a Hubble time (Rephaeli & Persic 1992) so it would remain hot today.

There have been several searches for diffuse X-ray emission from SCs. Although Murray et al. (1978) claimed that UHURU data showed evidence for ISC emission, subsequent observations and analyses have not supported this claim (Pravdo et al. 1979; Persic, Rephaeli, & Boldt 1988; Persic et al. 1990). Using ROSAT PSPC data Bardelli et al. (1996) reported the detection of diffuse emission in the region between two clusters in the Shapley supercluster. On the other hand, Day et al. (1991) and Molnar & Birkinshaw (1998) have placed relatively strong upper limits on the 2 – 10 keV diffuse emission in this supercluster. While the current upper limits are interesting, they still leave room for a substantial amount of hot ISC matter and more sensitive searches are underway. Particularly intriguing is the result from the cross-correlation analysis of the ROSAT All-Sky Survey with the Abell catalog. Soltan et al. (1996) found that Abell clusters seemed to be associated with diffuse X-ray emission with an extent of  $\sim 20$  Mpc. It is tempting to associate this emission with hot ISC gas; although, there is as yet no direct evidence for this.

Hot ISC gas can also leave its signature on the Cosmic Microwave Background



(CMB) via the Sunyaev-Ze'dovich (SZ) effect. Hogan (1992) suggested that the SZ effect in superclusters might account for the fluctuations in the CMB observed by the COBE satellite; however, subsequent analyses have shown that this is not the case (Boughn & Jahoda 1993; Bennett et al. 1993). Molnar and Birkinshaw (1998) used the lack of an SZ effect in the COBE DMR data to place an additional constraint on the ISC gas in the Shapley supercluster while Banday et al. (1996) found no evidence for the SZ effect in superclusters using a statistical cross-correlation analysis. Because of the large intrinsic fluctuations in the CMB, searches for the SZ effect in SCs will undoubtedly result in upper limits until the next generation of CMB satellites provide adequate frequency coverage to resolve the two effects.

Searches for ISC gas in the local supercluster (LSC) have the advantage of much higher integrated signal, however, are frustrated by the presence of other large-scale structure in the X-ray sky. Shafer (1983) and Boldt (1987) reported evidence for large-scale structure in the HEAO 1 A2 2 – 10 keV data which is roughly consistent with either the Compton-Getting dipole expected from the Earth's motion with respect to the CMB or general emission from the direction of the center of the LSC. Subsequent analyses (Shafer & Fabian 1983) demonstrated that Compton-Getting dipole adequately accounts for this large-scale structure; however, the direction of the dipole was determined to be in a somewhat different direction than that of the CMB dipole. Jahoda and Mushotzky (1989) found evidence for enhanced 2 – 10 keV emission from the direction of the Great Attractor which is in the same general direction as the Compton-Getting dipole. In addition, Jahoda (1993) has found evidence for high latitude 2 – 10 keV emission from the Galaxy as well as emission associated with the Supergalactic plane (the plane of the LSC), the latter of which is particularly relevant to the analysis presented in this paper.

In the following sections we present evidence that there is enhanced emission in the Supergalactic plane and that this emission is distinct from the other large-scale structures indicated above. To the extent that this is true, we will argue that the emission is diffuse and not associated with galaxies or other compact X-ray sources in the plane. It is, of course, possible that the emission is due to still larger scale structure of the type discussed by Miyaji & Boldt (1990) and Lahav, Piran, & Treyer (1997) or even to the chance alignment of fluctuations in the X-ray background (XRB); although, we argue that the latter is unlikely. These possibilities will be discussed in more detail below.

## 2. HEAO1 A2 2 – 10 keV X-ray Map

The HEAO1 A2 experiment measured the surface brightness of the X-ray background in the 0.1 – 60 keV band (Boldt 1987). The present data set was constructed from the output of two medium energy detectors (MED) with different fields of view ( $3^\circ \times 3^\circ$  and  $3^\circ \times 1.5^\circ$ ) and two high energy detectors (HED3) with these same fields of view. The data were collected during the six month period beginning on day 322 of 1977. Counts from the four detectors were combined and binned in 24,576  $1.3^\circ \times 1.3^\circ$  pixels in an equatorial quadrilateralized spherical cube projection on the sky (White & Stemwedel 1992). The combined map has a spectral bandpass (quantum efficiency  $\gtrsim 50\%$ ) of approximately 3 – 17 keV (Jahoda & Mushotzky 1989) and is shown in Galactic coordinates in Figure 1. For consistency with previous work all signals will be converted to equivalent flux in the 2 – 10 keV band.

The effective point spread function (PSF) of the map was determined by averaging the PSFs of 75 HEAO1 point sources (Piccinotti et al. 1982). The composite PSF is well fitted by a gaussian with a full width, half maximum of  $2.96^\circ$ . This value will be important in estimating the effective noise in the maximum likelihood fits of §3.4. Because of the pixelization, the PSF varies somewhat with location on the sky; however, this has little effect on noise estimates so we assume a constant PSF.

In order to remove the effects of both point source and large-scale structure, more than half the map was flagged and not included in the fits described in §3. The dominant feature in the HEAO map is the Galaxy (see Figure 1) so all data within  $20^\circ$  of the Galactic plane and, in addition, within  $30^\circ$  of the Galactic center were cut from the map. In addition,  $10^\circ$  diameter regions around 90 discrete X-ray sources with 2 – 10 keV fluxes larger than  $3 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$  (Piccinotti et al. 1982) were removed. The resulting “cleaned” map covered about 50% the sky. In order to identify additional point sources, the map itself was searched for “sources” that exceeded the nearby background by a specified amount. This was accomplished by first averaging each pixel with its 8 neighbors (note that the quadrilateralized cube format lays out the pixels on an approximately square array) and then comparing this value with the median value of the next nearest 16 pixels. Pixels within the flagged Galactic region are ignored. If the average flux associated with a given pixel exceeds the median flux of the background, then all 25 pixels are flagged and removed from further consideration. These flagged regions correspond approximately to a  $6.5^\circ \times 6.5^\circ$  patch. This procedure is not done iteratively, i.e. each comparison is made on the basis of the original map with only the Galaxy flagged. Cuts were made at several levels corresponding to average fluxes of from 3 to  $7 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ . The most extreme cut corresponds to an equivalent point source flux of  $3 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$  and results in 75% of the sky being

flagged. At this level, most of the “sources” cut are either noise fluctuations or fluctuations in the X-ray background. In any case, the results of §3.5 are largely insensitive to these cuts.

Only one large-scale correction to the map, the Compton-Getting dipole, was made a priori. If the dipole moment of the cosmic microwave background is a kinematic effect, as it has been widely interpreted (Bennett et al. 1996), then the X-ray background should possess a similar dipole structure (Compton-Getting effect) with an amplitude of  $4.3 \times 10^{-3}$ . As discussed in §1, evidence for this structure is found in the HEAO map (Shafer 1983; Shafer & Fabian 1983; Lahav, Piran, & Treyer 1997). The cleaned map was corrected for this effect; however, the results of §3.5 are the same even if the amplitude and direction of the dipole are fit from the data.

The presence of three other sources of large-scale structure in the X-ray map has been noted. A linear time drift in detector sensitivity (Jahoda 1993) results in effective large-scale structure of known form but unknown amplitude. In addition, the  $2 - 10$  keV background shows evidence of high latitude Galactic emission as well as emission associated with the Supergalactic plane (Jahoda 1993). Models for all three of these contributions are simultaneously fit to the data as is discussed in §3.4.

Because of the ecliptic longitude scan pattern of the HEAO satellite, sky coverage and, therefore, photon shot noise are not uniform. However, the mean variance of the cleaned, corrected map,  $2.0 \times 10^{-2} (TOT \text{ cts/sec})^2$ , is considerably larger than the mean variance of photon shot noise,  $0.67 \times 10^{-2} (TOT \text{ cts/sec})^2$ , where  $1 \text{ TOT ct/sec} \approx 2.1 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$  (Allen, Jahoda, & Whitlock 1994). This implies that the X-ray map is dominated by “real” structure (not photon shot noise). For this reason, we chose to weight the pixels equally in all subsequent analyses.

### 3. Modelling the Large-Scale Structure

#### 3.1. Instrument Drift

At least one of the A-2 detectors changed sensitivity by  $\sim 1\%$  in the six month interval of the current data set (Jahoda 1993). Because of the ecliptic scan pattern of the HEAO satellite, this results in a large-scale pattern in the sky which varies with ecliptic longitude with a period of  $180^\circ$ . If the drift is assumed to be linear, the form of the resulting large-scale structure in the map is completely determined. A linear drift of unknown amplitude is taken into account by constructing a sky map with the appropriate structure and then fitting for the amplitude simultaneously with the other parameters. We investigated the possibility of

non-linear drift by considering quadratic and cubic terms as well; however, the results of §3.5 were insensitive to this refinement.

### 3.2. The Galaxy

The X-ray background has a diffuse (or unresolved) Galactic component which varies strongly with Galactic latitude (Iwan et al. 1982). This emission is still significant at high Galactic latitude ( $b_{ll} > 20^\circ$ ) and extrapolates to  $\sim 1\%$  at the Galactic poles. We modeled this emission in two ways. The first model consisted of a linear combination of a secant law Galaxy with the Haslam 408 *GHz* full sky map (Haslam et al. 1982). The latter was included to take into account X-rays generated by inverse Compton scattering of CMB photons from high energy electrons in the Galactic halo, the source of much of the synchrotron emission in the Haslam map. We find only marginal evidence for such emission (§3.5). As an alternative Galaxy model we also considered the two disk, exponentially truncated model of Iwan et al. (1982). The analysis of §3.5 shows significant X-ray emission correlated with either of these models.

### 3.3. The Local Supercluster

The level of emission from the plane of the LSC reported in this paper is barely above the noise ( $S/N \sim 3$ ). Therefore, detailed models of LSC emission are not particularly useful. We chose a simple "pillbox" model, i.e. uniform X-ray emissivity,  $\epsilon_x$ , within a circular disk of radius  $R_{SC}$  and height (thickness),  $H_{SC}$ . The X-ray intensity in a particular direction is then proportional to the pathlength,  $L$ , through the LSC disk, i.e.,  $I_x = \epsilon_x L / 4\pi$ . The nominal location of the LSC disk was chosen to be in the Supergalactic plane (Tully 1982) with a nominal center in the direction of the Virgo cluster (M87); however, these positions were allowed to vary from their fiducial locations. The radial position of the Galaxy was assumed to be  $0.8 R_{SC}$  from the center of the LSC, i.e., near the edge. The value of  $R_{SC}$  is left as a scale parameter in the final results; however, the dependence on the diameter of the LSC was investigated by varying the radial position of the Galaxy within the LSC disk (see §4.5). The thickness to diameter ratio,  $H_{SC} / 2 R_{SC}$ , was also varied; however, we considered the nominal value to be  $1/8$  which is consistent with the distribution of galaxies in the LSC (Tully 1982). In any case, as is true for the Galaxy model, the results of §3.5 are not overly sensitive to these model parameters.

### 3.4. Analysis

Combining the three above models with a uniform X-ray background we arrive at the following 5 parameter expression for the “diffuse” X-ray intensity,  $X_i$ , in the  $i^{\text{th}}$  sky pixel,

$$X_i = a_1 + a_2 \times P_i + a_3 \times T_i + a_4 \times S_i + a_5 \times H_i \quad (1)$$

where the first term represents the intensity of the uniform X-ray background,  $P_i$  represents the intensity due to the LSC “pillbox” normalized to a pathlength of 1  $R_{SC}$ ,  $T_i$  is the pattern on the sky caused by a linear drift in detector sensitivity,  $S_i$  is emission proportional to the cosecant of Galactic latitude normalized to the Galactic pole,  $H_i$  is the antenna temperature (in  $^{\circ}K$ ) of the 408  $MHz$  Haslam map, and  $a_k$  are the 5 free parameters.  $P_i$ ,  $S_i$ , and  $H_i$  are convolved with the PSF of the observed map. Since, as discussed above, each pixel was weighted equally, the least squares fit to the 5 parameters is obtained by minimizing an effective  $\chi^2$ ,

$$\chi^2 = \sum_i (x_i - \sum_m a_m X_{m,i})^2 \quad (2)$$

where  $x_i$  is the observed X-ray intensity in the  $i^{\text{th}}$  pixel,  $X_{m,i}$  is the  $i^{\text{th}}$  pixel of the  $m^{\text{th}}$  parameter map (i.e.,  $X_{1,i} = 1$ ,  $X_{2,i} = P_i$ ,  $X_{3,i} = T_i$ ,  $X_{4,i} = S_i$ , and  $X_{5,i} = H_i$ ), and  $a_m$  is the  $m^{\text{th}}$  fit parameter. The sum,  $\sum_i$ , is over all unflagged pixels in the cleaned HEAO map.

The errors in the fit due to uncorrelated shot noise are easily computed by (see for example Press et al. 1986)

$$\sigma_k^2 = \sum_{m,n} C_{k,m} C_{k,n} \sum_i \sigma_i^2 X_{m,i} X_{n,i} \quad (3)$$

where  $1 \leq k, m, n \leq 5$  indicate the 5 fit parameters and  $\sigma_i$  indicates the photon shot noise in the  $i^{\text{th}}$  pixel.  $C_{m,n}$  is the inverse of the matrix  $A_{m,n}$  which is defined as  $A_{m,n} = \sum_i X_{m,i} X_{n,i}$ .

The intrinsic fluctuations in the X-ray background (XRB) can be thought of as an additional source of noise. The errors in the fit parameters induced by this noise are more problematic since XRB fluctuations exhibit pixel to pixel correlations due to the finite PSF of the detectors and the clustering of X-ray sources. In addition, these fluctuations may not be uniform on the sky. If  $R_{i,i'} = \langle \delta I_{x,i} \delta I_{x,i'} \rangle$  represents the auto-correlation function (ACF) of the intensity of the XRB then it is straightforward to show that the corresponding errors in the fit parameters are given by

$$\sigma'_k{}^2 = \sum_{m,n} C_{k,m} C_{k,n} \sum_{i,i'} R_{i,i'} X_{m,i} X_{n,i'} \quad (4)$$

As an estimate of these errors we will, in the analysis to follow, assume that the fluctuations are uniform. This assumption was checked after the fact by evaluating the

post-fit residual *rms* fluctuations. After accounting for photon counting noise, there is no evidence for significant variation of the intrinsic fluctuations across the sky. In particular, the *rms* sky fluctuations near the plane of the LSC was within 3% of the *rms* over the entire sky. Figure 2 is the ACF of the X-ray map (map#2 - see §3.5) corrected for large-scale structure (i.e., a uniform X-ray background, the Compton-Getting dipole, Galaxy and LSC emission, and instrumental drift). The point at  $\theta = 0$  has been corrected for photon shot noise. If correlated structure on small angular scales is entirely due to a gaussian PSF, i.e.,  $PSF \propto e^{-\theta^2/2\sigma_p^2}$ , it is straightforward to show that the ACF has the form,  $R_{i,i'} = R_0 e^{-\theta_{i,i'}^2/4\sigma_p^2}$  where  $\theta_{i,i'}$  is the angle between the  $i^{th}$  and the  $i'^{th}$  pixels. The dashed curve in Figure 2 is this functional form. Note that  $\sigma_p$  is not a fit parameter but is determined by the profiles of point sources (see §2). While this curve is a good fit to the data for  $\theta < 4^\circ$ , the data for  $4^\circ \lesssim \theta \lesssim 10^\circ$  lie somewhat above the curve. Whether or not this is due to clustering of the X-ray background or to an improperly modeled PSF is not clear; however, it seems unlikely that the PSF extends out to  $10^\circ$ . In any case, we have also modeled the ACF as the sum of an exponential and a term proportional to  $(\theta^2 + \theta_0^2)^{-1}$  to account for the possibility of large-scale clustering. The solid curve in Figure 2 represents this four parameter fit.

Since the photon shot noise and sky fluctuations are uncorrelated, the two sources of errors should be added in quadrature, i.e.,  $\sigma_{tot}^2 = \sigma^2 + \sigma'^2$ .

### 3.5. Results

The results of the analysis described in §3.4 for two different cleaning windows of the map are given in Table 1. Map#1 is minimally windowed, i.e. the Galaxy pixels are flagged as well as the regions around the Piccinotti sources (see §2). In addition, 20 "sources", i.e., isolated regions of high flux, were flagged (see §2); however, these comprised only 0.21 sr, i.e. 1.6% of full sky. This cleaned map contains 11637 pixels which corresponds to a 47% sky coverage. Map#2 was subjected to more aggressive "source" cleaning and contains 8153 pixels, i.e. 33% sky coverage.

The three errors listed in Table 1 are for photon shot noise only and for shot noise plus the estimated noise for fluctuations in the XRB according to the two models of Figure 2 (see §3.4). For shot noise alone,  $\chi_\nu^2$  is quite large which is simply an indication of the importance of fluctuations in the XRB. When these fluctuations are included  $\chi_\nu^2$  drops considerably. The fact that in the latter case  $\chi_\nu^2 \sim 1$  is not particularly significant since fluctuations in the XRB were estimated from excess noise in the map. The effective number of degrees of freedom is considerably less (by about a factor of 4 to 5) than the number of

pixels since the largest component of the noise is correlated.

It is clear from Table 1 that the parameters from the two fits are consistent with each other and indicate that all parameters except  $a_5$  are significantly different from zero. From Table 2 we see that fit parameters are not strongly correlated with each other. Of particular significance to this paper is that the flux associated with the supercluster is positive by  $\sim 3\sigma$  even when the fluctuations in the XRB are taken into account. A test for the statistical significance for this result is discussed in §4.4. Taken at face value, the fits in Table 1 indicate that diffuse X-ray emission from the local supercluster has been detected. However, a great many checks must be made on robustness of this result: e.g., whether or not the signal comes from a few strong point sources located near the supergalactic plane; whether or not the signal is due to X-ray emitting galaxies distributed in the LSC; whether or not the signal arises from a chance alignment of fluctuations in the X-ray background; whether or not the result is sensitive to the pillbox model parameters; etc. The next section contains a detailed discussion of these issues.

While photon counting noise is smaller than intrinsic sky fluctuations, it is not negligible and, furthermore, varies by a factor of 2 over the sky. The resulting total variance, shot noise plus sky fluctuations, varies by  $\sim \pm 20\%$  from the mean. One might argue that it is better to weight the individual terms in  $\chi^2$  (see eq. 2) inversely with the total variance appropriate for each pixel. Certainly this should reduce somewhat the error in the fit. If the analyses are performed in this way the fits for the the local supercluster parameter,  $a_2$ , decrease by an average of about 4% while the errors in the fits decrease by an average of about 2%, i.e. the results are not significantly different. We prefer to weight the pixels equally to minimize any systematic structure in the map that happens to be correlated with the noise pattern.

## 4. Systematics

### 4.1. The Galaxy

Even though the plane of the Galaxy, a strong source of X-ray emission, was removed from the map (see §2), high Galactic latitude emission is large enough to be a potential source of error. However, the planes of the Galaxy and the LSC are nearly perpendicular and the center of the LSC is nearly at the Galactic pole. It is these fortuitous circumstances that result in nearly uncorrelated Galaxy and LSC fit parameters (see Table 2). As a consequence, one expects that the fit to LSC emission will be nearly independent of Galactic emission. As an alternative Galaxy model we considered the two disk, exponentially

truncated model of Iwan et al. (1982). The  $\chi^2$  for the fits with this model were slightly worse while the LSC fit parameters were essentially unchanged ( $\delta a_2 \lesssim 3\%$ ). Even if the Galaxy model is left out of the fit entirely, the resulting LSC emission changes by only  $\sim 25\%$ ; however, the  $\chi^2$  is significantly worse. Therefore, we consider it unlikely that the supercluster emission found above is due to Galaxy contamination.

#### 4.2. Compton-Getting Dipole

As discussed in §2, the X-ray map was corrected for the Earth's motion relative to the average rest frame of the distant Universe as defined by the CMB dipole. This is justified since the bulk of the X-ray background arises from sources at high redshift ( $z \gtrsim 1$ ). The amplitude of the X-ray dipole is easily computed from the CMB dipole and the spectrum of the X-ray background, i.e.,  $\delta I_x/I_x = 4.3 \times 10^{-3}$  which is  $\sim 3.4$  times larger than the CMB dipole. In addition, it is likely that X-rays trace the asymmetric mass distribution which created our peculiar velocity, and one would expect an intrinsic dipole moment in the XRB which is more or less aligned with the Compton-Getting dipole. However, it seems unlikely that the former will be as large as the latter. From unified models of the XRB (e.g. Comastri et al. 1995), less than 0.2% of the XRB background arises from sources within 50 Mpc and with fluxes  $< 3 \times 10^{-11} \text{ ergs}^{-1} \text{ cm}^{-2}$ . Lahav, Piran, and Treyer (1997) demonstrated that the large-scale structure dipole can be comparable to the Compton-Getting dipole if one assumes, contrary to observations, unevolving X-ray luminosity and no upper limit on source flux. It is unlikely that their calculation is relevant to our analysis; never-the-less, we considered the possibility that the dipole correction made to the data is in error. If a dipole term is included in the fit, it is also not strongly correlated with the "pillbox" term and the resulting LSC emission changes by only  $\sim 15\%$  for Map#1 and by  $\sim 5\%$  for Map#2. The  $\chi^2$ 's were only marginally better if these terms are included. It is interesting that the resulting fit dipoles for the two maps agree within errors with that predicted for the Compton-Getting dipole. For Map#2, the fit dipole amplitude is  $\delta I_x/I_x = 5.3 \pm 1.8 \times 10^{-3}$  while the direction is  $\sim 19^\circ$  from the CMB dipole which is well within the directional error. For Map#1 these values are  $\delta I_x/I_x = 2.7 \pm 1.8 \times 10^{-3}$  and  $\sim 35^\circ$  also consistent with the Compton-Getting dipole. We find the results of the dipole fits significant in that they indicate that large-scale structure can be detected at this level. If the dipole term is excluded altogether from the fit, the values of LSC emission for the two maps increase by about 30%.



### 4.3. Timedrift

The timedrift fit parameter in Table 1 corresponds to somewhat less than 2% of the XRB during the six month interval of the observations and, therefore, is also of potential concern. However, from Table 2 it is evident that this fit parameter is essentially uncorrelated with the LSC parameter indicating that our estimate of LSC emission is also not very sensitive to drift of detector sensitivity. In the case that the linear timedrift model is removed from the fit, the LSC parameter changes by  $< 5\%$  while the  $\chi^2$ 's are significantly worse. In order to test the limitations of the linear timedrift model we included cubic and quadratic terms as well. The solutions and  $\chi^2$ 's were essentially unchanged. We conclude that detector drift cannot account for the observed emission from the LSC.

The Galaxy, the dipole, and the effects of timedrift are all more or less orthogonal to the LSC. In fact, if we remove all three of these items from the analysis the fit to LSC emission changes by only 4% for Map#2 and by 20% for Map#1.

### 4.4. The XRB

It is now generally accepted that the X-ray background is composed of discrete sources (Hasinger et al. 1993; Georgantopoulos et al. 1997). Source confusion due to the finite resolution of the map along with inherent clustering of sources result in fluctuations in the XRB with an angular scale of about  $3^\circ$  and an amplitude of about 3% of the background. On the other hand, the implied LSC emission is about 1% of the XRB so it is important to consider whether or not chance alignments of these fluctuation could account for it.

To the extent that fluctuations in the XRB can be modeled as in §3.5, the above analysis indicates that the fit to LSC emission is significant at the  $\sim 3\sigma$  level. As an independent check we repeated the fits for 5000 pillbox models with a uniform distribution of orientations in the sky. Because of the extensive windowing of the Galactic plane, models lying within  $30^\circ$  of the Galactic plane were disregarded. Also because of the "detected" LSC emission, models lying within  $30^\circ$  of the LSC plane were also excluded. For Map#1, the amplitude of LSC emission in Table 1 exceeds those of 97% of the trials while 93% of the  $\chi^2$ 's of the trial fits exceed the value in the table. Only 2.6% of the trials have LSC emission greater and  $\chi^2$ 's less than those listed in Table 1. The results for Map#2 are even stronger. The LSC emission exceeds the fits of 99% of the trials while the  $\chi^2$  is exceeded by 97% of the  $\chi^2$ 's of the trials. Only 0.7% of the trials have LSC emission greater and  $\chi^2$ 's less than the values listed in Table 1. If one includes the models that lie within  $30^\circ$  of the plane of the LSC, the results for Map#2 are essentially the same while for Map#1 4.6% of the

trials have LSC emission greater and  $\chi^2$ s less than those listed in Table 1. Since Map#1 has significantly more “hot spots” than the more heavily windowed Map#2, it is perhaps not surprising that the former is more susceptible to chance alignments of these “sources” resulting in spuriously large amplitudes of emission associated with several pillbox models. We conclude that at the  $\sim 99\%$  confidence level fluctuations in the XRB are not responsible for the observed signal. This corresponds to a  $2\sigma$  to  $3\sigma$  effect and is roughly consistent with the estimates of the errors indicated in Table 1.

#### 4.5. Pillbox Model

The pillbox model for the LSC is highly simplistic; however, more refined models seem unwarranted considering the relatively low signal to noise ( $\lesssim 3\sigma$ ) indicated in Table 1. Nevertheless, several important checks of the model can be made. The checks illustrated in the figures below are for the more extensively windowed Map#2; however, the conclusions are essentially the same for both maps.

Figure 3 is a plot of the LSC emission fit for a series of pillbox models lying in the supergalactic plane but with centers rotated by angles in steps of  $30^\circ$  from the nominal center of the LSC in Virgo. It is clear that the largest emission signals occur when the model center is near the nominal direction. In addition, the  $\chi^2$ s of the fits are significantly worse for models rotated by angles  $\geq 60^\circ$ . The lowest  $\chi^2$  occurs (for both windowed maps) at an angle of  $-23^\circ$  for which the LSC emission is somewhat larger; however, the differences from the Virgo centered model are not significant.

The dependence of the results on the vertical position of the Galaxy within the disk of the LSC is illustrated in Figure 4. The vertical position is expressed in terms of the disk thickness,  $H_{SC}$ , so  $\pm 0.5$  represents the top and bottom of the disk. Again the nominal central position yields the largest LSC emission with the  $\chi^2$ s of the fits increasing significantly at the extremes.

Figure 5 illustrates the dependence of results on the radial position of the Galaxy in the LSC. Position is expressed in units of the supercluster radius. The nominal value is 0.8. It is clear from the figure that the largest LSC emission is found for models with the Galaxy near the edge of the LSC (note: negative values indicate models with centers in the direction opposite Virgo). The model with the nominal radial position has the smallest value of  $\chi^2$  while models with radial positions  $\leq 0.5$  have significantly larger  $\chi^2$ s. For this test the results for Map#1 differ somewhat in that models with radial positions  $\geq 0.2$  have reasonable  $\chi^2$ s; however, the fit LSC emission was comparable for all these models.

In order to test specifically whether or not a few isolated “hot spots” in the supergalactic plane are responsible for the signal, the data is binned according to that emission predicted from the pillbox model and then plotted in Figure 6 as a function of emission predicted from the model. The scale of the predicted emission is taken from Table 1 and the data is corrected for all fit large-scale structure except for LSC emission. If the signal is due to hot spots in the direction of the center of the LSC, the extreme right hand data point would fall well above the unity slope curve while other points would fall well below the curve. Within the limitations of signal to noise, it appears that this is not the case. Of course, the disposition of the data is sensitive to the binning. While finer scale binning does show a great deal of scatter, the linear trend is clear. The data from Map#1 shows the same trend with a bit more scatter.

Finally we investigate how sensitive the results are to varying the thickness to diameter ratio of the pillbox model. The answer is “not very”. For Map#1, only for ratios  $H_{SC}/D_{SC}$  less than  $1/12$  and greater than  $1/4$  are the  $\chi^2$ s of the fits significantly worse. For Map#2 these values are  $1/16$  and  $1/2$ . The values of LSC emission decrease somewhat as  $H_{SC}/D_{SC}$  increases; however, the statistical significance of detection is roughly the same for all models in this range. One can only deduce a very rough value of the thickness to diameter ratio from the data and must rely on the optical structure of the LSC (Tully 1982). Clearly, the more important aspect of the models is that the emission is enhanced in the general direction of Virgo.

#### 4.6. Windowing

As discussed in §2 pixels of the X-ray map were flagged if they were: 1) too close to the plane of the Galaxy; 2) if they were near a strong X-ray source; or 3) if they were near a positive fluctuation in the XRB. Failing to remove the strong X-ray sources results in a very poor fit,  $\chi^2_\nu > 30$ ; therefore, these cuts are absolutely necessary. On the other hand, the results of §3.5 are relatively insensitive to the other two cuts. The level of LCS emission changes by less than 30% if the Galactic plane cut is varied between  $20^\circ$  and  $50^\circ$  (the smallest fit value of LSC emission is only 5% less than that of Table 1). Similarly, the fit LSC emission does not change significantly from the minimally windowed Map#1 to a map with only 20% full sky coverage.

#### 4.7. X-ray Auto-Correlation Function

As a check on how well the modeled structure matches the X-ray sky, the auto-correlation function (ACF) of the map was compared with that predicted by the model. One might expect that the unity values of the  $\chi^2$ 's of Table 1 indicate that the fit is quite good. However, recall that this value was forced by assuming that all the excess variance was due to fluctuations in the XRB. If, on the other hand, the excess were due to unmodeled large-scale structure then the modeled ACF would not fit the data. Figure 7 shows that the ACF is well modeled and that there appears to be little other large-scale structure in the map. The solid curve of Figure 2 was taken as the model of the small-scale fluctuations in the XRB. For  $\theta > 10^\circ$  the data is binned in  $13^\circ$  bins to reduce scatter.

#### 4.8. Point Sources

Even if the above arguments indicate that there is X-ray emission associated with the plane of the LSC, it is not at all clear that this emission originates from diffuse gas. After all, there are a great many galaxies and several clusters in this plane and all of these emit X-rays at some level. However, there are several indications that it is not the case that faint sources contribute significantly to the X-ray emission in the LSC plane. At a distance of 20 *Mpc* the cutoff flux of the present map ( $3 \times 10^{-11} \text{ ergs s}^{-1} \text{ cm}^{-2}$ ) corresponds to a luminosity of  $\sim 10^{42} \text{ erg s}^{-1}$ ; therefore, only relatively weak (compared to AGN) sources could contribute. The observed upper limit of the average 2 – 10 *keV* emissivity of such sources in the local ( $z \lesssim 0.1$ ) universe is  $4 \times 10^{38} h \text{ erg s}^{-1} \text{ Mpc}^{-3}$  (Miyaji et al. 1994) where  $h$  is the Hubble constant in units of  $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . On the other hand the pillbox model of the LSC and the amplitude of the X-ray flux in Table 1 imply an average X-ray emissivity of  $3.0 \times 10^{39} (R_{SC}/20 \text{ Mpc})^{-1} \text{ erg s}^{-1} \text{ Mpc}^{-3}$  (see §6). Thus for a Hubble constant of  $60 \text{ km s}^{-1} \text{ Mpc}^{-1}$  the ratio of the observed LSC emissivity to the average emissivity of weak sources is  $\gtrsim 12$ . For an LSC collapse factor is  $\sim 10$ , the observed emissivity could be due to weak sources without seriously violating this constraint.

However, unified models of the XRB indicate that it is unlikely that weak sources make a significant contribution to the average X-ray emissivity. For example, the model of Comastri et al. (1995) imply an average, local 2 – 10 *keV* emissivity of  $7.6 \times 10^{38} h \text{ erg s}^{-1} \text{ Mpc}^{-3}$  which is consistent with the observed value ( $8.6 \pm 2.4 \times 10^{38} h \text{ erg s}^{-1} \text{ Mpc}^{-3}$ ) derived by Miyaji et al. (1994) from a cross-correlation analysis of the HEAO-1 A2 map with galaxies from the IRAS survey. The Comastri model (by design) accounts for the entire XRB. According to this model, weak sources make a small contribution to the local emissivity, i.e.  $< 7.6 \times 10^{37} h \text{ erg s}^{-1} \text{ Mpc}^{-3}$ . For  $h = 0.6$  this is a factor of  $\sim 65$  less than inferred

for the LSC. If weak sources account for the LSC emissivity, then either Comastri et al. (1995) seriously underestimate their numbers or the LSC collapse factor is much larger than observed for visible galaxies. While the above argument is suggestive, it is based on a unified AGN model which is by no means certain. In fact, there is some speculation that weak sources do make a significant contribution to the XRB (Yi & Boughn 1998; Di Matteo & Fabian 1997). Stronger constraints on the point source contribution to LSC emissivity come from the consideration of two source catalogs, the Nearby Galaxies Catalog (NBG) (Tully 1988) and the ROSAT All-Sky Survey Bright Source Catalog (Voges et al. 1996).

There are 2367 galaxies in the NBG catalog which consists of all galaxies with known velocities  $\leq 3000 \text{ km s}^{-1}$ . This catalog is dominated by two data sets: the Shapely-Ames sample and the all-sky survey of neutral hydrogen. Although the catalog has severe incompleteness problems at velocities above  $2000 \text{ km s}^{-1}$ , the coverage is homogeneous across the unobscured part of the sky (Tully 1988). In any case, if point X-ray sources associated with galaxies in the LSC are an important source of X-ray emissivity it seems reasonable that much of the emission would be associated with the galaxies in this catalog. To check this possibility, the X-ray map was further cleaned by removing  $\sim 15$  square degree regions (somewhat larger than the PSF of the map) at the location of all of catalog galaxies. Many of these regions lie in already windowed sections of the map. After the additional cuts the sky coverage was reduced to 26% for Map#1 and 18% for Map#2. The reduced coverage results in an increase in noise; however, the levels of LSC emission are still marginally significant ( $2 \sigma$  and  $1.5 \sigma$  for Map#1 and Map#2 respectively) and are somewhat larger than but consistent with the values in Table 1.

Another check of the level of contribution of galaxies from the NBG catalog was made by fitting the LSC pillbox plus a monopole to the  $15 \text{ deg}^2$  regions surrounding the galaxies but with the appropriate windowing of Maps#1 and #2. Before the fits the maps were corrected for a dipole, the Galaxy and instrumental drift. The sky coverage for these fits was only 21% and 15%; however, if these regions dominate LSC emission then the amplitude of the fit should be considerably larger than in Table 1. This was not the case. In fact, the fit amplitudes of LSC emission are essentially the same as those in Table 1. Although the above tests are consistent with diffuse LSC emission, the Tully galaxies (smoothed by the PSF) occupy a great deal of the LSC plane and so this conclusion must be tempered.

One final check on the galaxy contribution was to generate a map by assigning an X-ray flux to each galaxy, convolve the resulting map with the PSF, and then apply the windowing appropriate for Maps#1 and #2. The X-ray flux of the galaxies was obtained by cross-correlating the X-ray map with an appropriately smoothed map of galaxy number density. This was done in four different distance bins ( $0 - 10$ ;  $10 - 20$ ;  $20 - 30$ ; and

30 – 50 *Mpc*) in order to account for distance dependence of flux. Only for the first bin was the correlation statistically significant. The X-ray emission from galaxies was determined using the  $1\sigma$  upper limits of the cross-correlation for the appropriate distance bin. The linear regression applied to the resulting maps yields upper limits to LSC emission which are a factor of 3 below the levels of Table 1. This result is another indication that X-ray emission from galaxies is not the major component of X-ray emission from the LSC plane.

A more direct indication of the contribution of point sources is the ROSAT All-Sky Survey (RASS) Bright Source Catalog (Voges et al. 1996). There are 18,811 sources in this catalog down to a 0.1 – 2.4 *keV* flux limit of 0.05 *cts/s* ( $3 \times 10^{-13}$  *erg s<sup>-1</sup> cm<sup>-2</sup>* for a photon spectral index of  $\alpha = -2$  where  $dN/dE \propto E^\alpha$ ). At a brightness limit of 0.1 *cts/s* (8,547 sources) the catalogue represents a sky coverage of 92%. Two hardness ratios, *HR1* and *HR2*, are defined by  $HR1 = (B - A)/(B + A)$  and  $HR2 = (D - C)/(D + C)$  where *A*, *B*, *C*, and *D* are the count rates in passbands that correspond roughly to 0.1 – 0.4 *keV*, 0.5 – 2.0 *keV*, 0.5 – 0.9 *keV*, and 0.9 – 2.0 *keV* (Snowden et al. 1995). The average *HR2* hardness ratio of the sources corresponds to a photon spectral index of  $\alpha \sim -2$ ; although, there are certainly sources that are much harder as well as sources that are much softer than this spectrum. For  $\alpha = -2$ , the catalog limit corresponds to a 2 – 10 *keV* flux of  $2 \times 10^{-13}$  *erg s<sup>-1</sup> cm<sup>-2</sup>* which is about two orders of magnitude below the Piccinotti et al. (1982) sources (see §2). If there is a significant population of relatively faint ( $3 \times 10^{-13}$  to  $3 \times 10^{-11}$  *erg s<sup>-1</sup> cm<sup>-2</sup>*) sources in the LSC, then a large fraction of these should show up in the Bright Source Survey. Even though the completeness level is not entirely uniform, the catalog can still be used to give an indication of the level contamination by point sources. There are too many RASS sources to simply window them from the HEAO map ( $3^\circ$  cuts around each source would window the entire map); however, there are several ways of testing for the effects of RASS point sources.

To check the contamination due to relatively bright sources or clusters of sources we constructed a B-band (0.5 – 2.0 *keV*) map of RASS sources convolved with the HEAO PSF. If the resulting B-band flux in any pixel was greater than 0.1 *ct/sec* (for  $\alpha = -2$  this corresponds to a flux of  $1 \times 10^{-12}$  *erg s<sup>-1</sup> cm<sup>-2</sup>*) then a  $15 \text{ deg}^2$  region about the pixel was windowed from the two previously windowed HEAO maps, i.e., Maps#1 and #2. Note that a single source with a flux of 0.9 *ct/sec* is at the cutoff flux after smoothing with the PSF. The resulting heavily windowed maps, Map#1' and Map#2', had sky coverages of 22% and 17% respectively. When the linear regression of §3.4 was performed on these two maps the fits to LSC emission were somewhat larger but not significantly different than the fits of Table 1. The errors in the fits were about 50% larger due to the reduced sky coverage. Similar results were obtained when the RASS cutoff flux level was varied as well as for windowing individual sources (i.e. not convolved with the PSF) with B-band fluxes

above a cutoff level. These results indicate that the LSC emission indicated in Table 1 is not due to the brighter of the RASS sources.

As another check on contamination, every source in the RASS catalog was assigned a  $2 - 10$  keV flux from its B-band flux by assuming a spectral index of  $-1 < \alpha < -3$  which was deduced from *HR2* hardness ratio. For faint sources the quantity *HR2* is quite noisy and the computed value of  $\alpha$  might be either larger than -1 or smaller than -3. For these sources  $\alpha$  was simply forced to be -1 or -3 which we consider to the limits of the range for nearly all X-ray sources. The B-band fluxes were corrected for Galactic extinction using HI column density maps (Stark et al. 1992; Dickey & Lockman 1990) and the absorption coefficients of Morrison and McCammon (1983). These corrections made little difference and, in any case, are probably less important than internal extinction in the sources themselves. The resulting  $2 - 10$  keV flux map was then convolved with the HEAO PSF and subtracted from the HEAO maps, Map#1 and Map#2. The linear regressions applied to these corrected maps implied LSC emission somewhat larger than but not significantly different from the values in Table 1.

As an upper limit to the contamination by RASS sources we applied the above map correction assuming that every source has a very hard spectrum, i.e.  $\alpha = -1$ . The linear regression fit to Map#2 was essentially unchanged while the LSC emission fit to Map#1 was reduced by about 40%. Assuming every source has the average spectral index, i.e.  $\alpha = -2$ , yields results that are virtually indistinguishable from those of Table 1.

At the catalog limit, 0.05 cts/sec, the coverage is probably less uniform than at a limit of 0.1 cts/sec; therefore, we repeated the above corrections for the brightest 8547 RASS sources ( $> 0.1$  cts/sec). The results were virtually unchanged.

Because of the effects of non-uniform coverage and imperfect knowledge of the spectra of individual sources, the above source corrections to the  $2 - 10$  keV flux are not particularly accurate. On the other hand, they do indicate that the emissivity of weak X-ray sources in the LSC is about an order of magnitude less than those implied in Table 1 and we conclude that those results are not contaminated by point sources.

#### 4.9. Clusters of Galaxies and the Great Attractor

It is well known that rich clusters of galaxies are strong X-ray emitters and, therefore, are a potential source of contamination. Distant clusters are indistinguishable from the point sources discussed above. In addition, 30 bright, nearby clusters including Virgo, Coma and Centarus are among the Picinotti et al. (1982) sources and have already been

windowed from the map. However, extended emission associated with nearby less compact clusters of galaxies might be considered a possible source of contamination.

Ebeling et al. (1997) used the ROSAT Brightest Cluster sample to fit a Schechter luminosity function to clusters and obtained a  $2 - 10$  keV  $L^*$  of  $1.2 \times 10^{45}$  erg s<sup>-1</sup> and a power law exponent of -1.51. Using these values, the implied total  $2 - 10$  keV emissivity is  $\epsilon_x = 1.3 \times 10^{38}$  erg s<sup>-1</sup> Mpc<sup>-3</sup> which is a factor of 25 less than that implied by the values of Table 1 (see §6). On the other hand, the luminosity of the Virgo cluster is  $\sim 1.4 \times 10^{43}$  erg s<sup>-1</sup> and sources this bright would be cut from the windowed data if they were within 60 Mpc. Again using the fit of Ebeling et al. (1997), the total emissivity of clusters less luminous than the Virgo cluster is  $\epsilon_x = 1.6 \times 10^{37}$  erg s<sup>-1</sup> cm<sup>-2</sup> Mpc<sup>-3</sup> or a factor of 200 less than the implied LSC emissivity. Even if this flux is increased by the collapse factor of 10, it is still considerably less than that inferred for the LSC (see §6).

As a further check on possible contamination by extended emission from galaxy clusters we extended the windowing of the X-ray map to include 15° diameter regions around the Virgo, Centarus, Coma, Fornax, and Ursa Major clusters as well as around the most dense regions of the Hydra, Pavo, Perseus, and Ophiuchus galaxy clouds (Tully 1988). Finally the diffuse emission found by Jahoda & Mushozky (1989) was eliminated by windowing a 40° diameter region about the Great Attractor. Fits of the LSC emission to these further windowed maps were only  $\sim 15\%$  less than those of Table 1 while the errors in the fit were, of course, somewhat larger. Therefore, there is no indication that the fits of Table 1 are contaminated by either the cores of clusters of galaxies or by diffuse emission from the Great Attractor.

The windowing of more extensive regions of galaxy clouds in the LSC would not be possible without cutting most of the plane of the LSC and, in any case, it is not clear one should distinguish such emission with diffuse emission in the LSC. This point is essentially the same as asking whether or not LSC emission is smooth or somewhat clumpy and will be addressed in §6 below; however, the bottom line is that the signal to noise is simply not high enough to be able to give a clear answer.

## 5. Sunyaev-Zel'dovich Effect in the LSC

If the diffuse X-ray emission in the LSC is due to Bremsstrahlung from a hot, ionized intergalactic medium then one might expect its signature to be imprinted upon the Cosmic Microwave Background (CMB) via inverse Compton scattering, i.e. the Sunyaev-Zel'dovich (SZ) effect (Sunyaev & Zel'dovich 1980). If the gas were uniformly distributed, the profile



in the CMB would be the same as in the X-ray except with a negative amplitude for observations on the Rayleigh-Jeans side of the blackbody spectrum. The CMB temperature decrement for radiation passing through a gas cloud of uniform electron density  $N_e$ , thickness  $L$ , and temperature  $T_e$  is given by (e.g. Hogan 1992)

$$(\delta T/T)_{CMB} \approx 4.0 \times 10^{-6} \beta l n_e t_e \quad (5)$$

where  $l = L/10 \text{ Mpc}$ ,  $n_e = N_e/10^{-5} \text{ cm}^{-3}$ ,  $t_e = kT_e/10 \text{ keV}$ ,  $\beta = (x \frac{e^x+1}{e^x-1} - 4)$ , and  $x = h\nu/kT_{CMB}$ . For  $L = 20 \text{ Mpc}$ ,  $N_e = 2.5 \times 10^{-6}$ , and  $kT_e = 10 \text{ keV}$ , the Rayleigh-Jeans decrement in the CMB is  $|\delta T/T| \sim 4 \times 10^{-6}$ . This value is somewhat smaller than the  $10^\circ$  scale fluctuations observed by the COBE DMR experiment, comparable to other large-scale structure in the microwave sky, e.g. high latitude Galactic emission and the expected intrinsic CMB quadrupole, and only marginally larger than the instrument noise in the DMR data (Bennett et al. 1996). Never-the-less, we performed the same type of analysis as for the X-ray background described in §3 above.

The four year 53 GHz DMR map was obtained from the COBE data archive in  $2.6^\circ \times 2.6^\circ$ , ecliptic, quadrilateralized spherical cube projection format (Bennett et al. 1996). This map was deemed more appropriate than the 31 GHz or 90 GHz maps because of a combination of low instrument noise, low Galaxy background, and moderately large  $\beta$  (see eq. 5). An 11 parameter linear regression similar to that of §3.4 was performed on the map after flagging all pixels within  $20^\circ$  of the Galactic plane and within  $30^\circ$  of the Galactic center. The fit parameters were a monopole, a dipole, a quadrupole, a secant law Galaxy model, and the amplitude of the canonical pillbox model of the LSC. As with the HEAO X-ray map, the sky coverage for the DMR maps and, hence, instrument noise are not uniform across the sky. In this case the instrument noise per pixel is larger than the intrinsic sky fluctuations so the contribution to  $\chi^2$  (see eq. 2) of each pixel is weighted inversely with noise variance of the pixel. However, the results did not change significantly when the analysis was repeated with equally weighted pixels. The formal fit to the pillbox amplitude (normalized to 1  $R_{SC}$ ) is

$$\delta T_{CMB} = -17 \pm 5 \mu K \quad (6)$$

where the uncertainty is statistical only and assumes uncorrelated instrument noise.

As mentioned above, this level is comparable to other systematic structure in the map and, therefore, should by no means be considered as a  $3\sigma$  detection. As an estimate of the significance of the result, the analysis was repeated for 5000 model pillboxes with a uniform distribution of orientations in the sky. As in §4.4 models lying within  $30^\circ$  of the Galactic and Supergalactic planes were disregarded. The amplitude of the SZ effect of eq. 6 is more negative than 82% of the rotated models indicating a significance of  $\sim 1 \sigma$ . On the other

hand, 80% of the  $\chi^2$ s of the trial fits exceed that of the fit of eq. 6 and 9% of the trials have more negative SZ fits and smaller  $\chi^2$ s than the LSC model. If one includes models that lie within  $30^\circ$  of the plane of the LSC these results do not change significantly. Nor are they changed for analyses in which the pixels are weighted equally.

Because of the low level of the signal only a few checks for systematics were made. The method of §4.5 was used to exclude the possibility that a single “hot” or “cold” source accounted for the signal. The LMC, SMC, and Orion Nebula were explicitly excluded with no significant change in the fit. Finally the three DMR maps (31, 53, & 90 GHz) were combined according to the prescriptions suggested by Hinshaw et al. (1996) to minimize the effect of the Galaxy. These combinations have larger effective noise and so result in larger statistical errors for the fits of the pillbox amplitude. The fit amplitudes varied from  $-5 \mu K$  to  $-22 \mu K$ . While it is clear the SZ effect due to hot gas in the LSC is not significantly detected, we note that the upper limit is consistent with the amount of hot, diffuse gas required to account for the diffuse X-ray emission discussed in §6. We do find it intriguing that the fits correspond to a decrement in the CMB as predicted by the SZ effect.

## 6. Discussion

If one takes seriously the hypothesis that hot, diffuse gas in the LSC is responsible for the diffuse X-ray emission claimed in §3, then the strength of the emission can be used to constrain the density and temperature of the gas. For simplicity assume a uniform, isothermal gas with electron temperature  $T_e$  and electron density  $N_e$ . Then the 2 – 10 keV X-ray intensity due to Bremsstrahlung is given by (e.g. Rybicki & Lightman 1979)

$$I_x = \epsilon_x L / 4\pi = 4.0 \times 10^{-9} n_e^2 t_e^{1/2} l \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \quad (7)$$

where  $L$  is the thickness of the emitting region,  $l = L/10 \text{ Mpc}$ ,  $n_e = N_e/10^{-5} \text{ cm}^{-3}$ , and  $t_e = kT_e/10 \text{ keV}$ . Primordial element abundances are assumed; however, the coefficient in eq. 7 only increases by a factor of 1.14 for solar abundance. From Table 1, the amplitude of the LSC emission normalized to 1  $R_{sc}$  is  $\sim 3.3 \times 10^{-2} \text{ TOT cts/s/4.5 deg}^2$  which corresponds for a 10 keV Bremsstrahlung spectrum to

$$I_x = 5.0 \times 10^{-10} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}. \quad (8)$$

From eqs. 7 and 8 (with  $L = R_{SC}$ )

$$N_e = 2.5 \times 10^{-6} (R_{SC}/20 \text{ Mpc})^{-1/2} (kT_e/10 \text{ keV})^{-1/4} \text{ cm}^{-3}. \quad (9)$$

The implied gas density is only weakly dependent on  $R_{SC}$  and  $T_e$ . Moreover, it is reasonable to assume that  $R_{SC} \sim 20 \text{ Mpc}$  (roughly the distance to the Virgo cluster) and

that  $kT_e \sim 10 \text{ keV}$ . A temperature much greater than 10 keV would exceed the virial temperature of the LSC while a temperature much less than 10 keV would have rendered the gas undetectable by HEAO. As a rough consistency check, the X-ray data were split into “soft” (2-5 keV) and “hard” (5-10 keV) components (Allen, Jahoda, & Whitlock 1994) and the “pillbox” fits of §3 repeated on the subdivided data sets. The ratio of the fit amplitudes (in cts/s) in these two bands is  $\dot{N}_{soft}/\dot{N}_{hard} \lesssim 1$ . Although the uncertainty in this ratio is considerable, it is consistent with an electron temperature of  $\gtrsim 10 \text{ keV}$  but inconsistent with temperatures  $< 3 \text{ keV}$ . Therefore, it seems unlikely that the implied electron number density could be much different than  $N_e \sim 2 \text{ to } 3 \times 10^{-6}$ . It is interesting to note that this value is roughly an order of magnitude larger than the mean number density of baryons in the universe and is consistent with a collapse factor of 10 which is roughly the aspect ratio of the LSC.

If this hot gas were distributed uniformly within a 40 Mpc diameter by 5 Mpc thickness supercluster, the implied total mass is  $\sim 4 \times 10^{14} M_\odot$ . From dynamical considerations, Shaya, Peebles, & Tully (1995) have estimated the total mass within a distance of 40 Mpc (about 40 times the volume of the LSC) is about  $7 \times 10^{15} M_\odot$ . On the other hand, total mass in stars in the same volume is about  $1 \times 10^{14} M_\odot$ , which is an order of magnitude too small to account for the baryonic matter which should be present. While the mass of the hypothetical hot gas in the LSC is insufficient to account for the dynamical mass in the local universe it may well make up the bulk of the baryonic matter.

These estimates rely on the gas being uniformly distributed. Since Bremsstrahlung is proportional to  $N_e^2$ , the emission is enhanced if there is any clumping of the gas. For example, if the gas is contained in 50% of the volume of the disk of the LSC, i.e. a clumping factor of 2, then the implied mean density decreases by a factor of  $1/\sqrt{2}$ .

As discussed in §5 above, the presence of hot, ionized gas is imprinted via the SZ effect on the cosmic microwave background. For 10 keV gas with a density of  $2.5 \times 10^{-6} \text{ cm}^{-3}$  and a thickness of 20 Mpc, the expected decrement in the CMB is  $\sim -11 \mu\text{K}$  for a Rayleigh-Jeans spectrum. While the fit of a pillbox LSC to the 53 GHz COBE map is consistent with this prediction, the systematic structure in the map is large and the agreement should be considered at best a  $1 \sigma$  confirmation.

If superclusters (SCs) with hot gas are common in the universe then their combined SZ effects would result in fluctuations in the CMB which might be confused with intrinsic CMB fluctuations (Hogan 1992). This has been demonstrated not to be the case for the COBE results (Boughn & Jahoda 1993; Bennett et al. 1993). To see how many SCs are allowed by this constraint suppose that a fraction  $f$  of all baryonic matter is contained in SCs with diameters of 40 Mpc and thicknesses 5 Mpc. Then the number density of SCs is

$n_{SC} = f/bV_{SC}$  where  $V_{SC}$  is the volume of an SC and  $b$  is the collapse factor. If each results in a temperature decrement of  $\delta T_{CMB} \sim 2$  to  $3 \mu K$  (for a path length equal to the thickness of the SC) then the *rms* fluctuations of a distribution of SCs should be  $\sim 2.5 \times \sqrt{N_{SC}} \mu K$  where  $N_{SC} \approx \pi R_{sc}^2 n_{SC} r$  is the number of SCs along the line of sight out to a distance  $r$ . To compare with the COBE DMR data for which  $\delta T_{rms} \sim 35 \mu K$  we set  $r \sim 400 Mpc$  at which a 40 Mpc SC would subtend an angle about equal to the COBE beam size. Even if  $f = 1$ , i.e. all the baryons in the universe are in the form of hot, diffuse gas in SCs, the fluctuations caused by the SZ effect would be  $\sim 7 \mu K$  or about 1/5 the level of the CMB fluctuations. In all likelihood, the fraction  $f$  is much smaller than unity. From the supercluster (SC) catalog of Batuski and Burns (1985), Rephaeli (1993) estimated the local density of SCs to be  $5 \times 10^{-8} h^3 Mpc^{-3}$ . If these SC's have volumes and densities of that inferred for the LSC, then only about 0.001 of the baryonic matter in the universe is contained in SCs, i.e.  $f = 0.001$ . Then the SZ fluctuations would be quite small,  $\lesssim 1 \mu K$ . In any case, the spectrum of SZ fluctuations differs significantly from those intrinsic to the CMB.

Another way to detect the presence of the SZ effect is via a spectral distortion of the CMB which is quantified by the Compton  $y$  parameter.  $y = \int (kT_e/m_e c^2) N_e \sigma_T dl$  where  $T_e$  is electron temperature,  $m_e$  is the electron mass,  $N_e$  is electron density,  $\sigma_T$  is the Thompson scattering cross-section, and  $l$  is path length (e.g. Rephaeli 1993). Assuming an isothermal gas this becomes  $y = (kT_e/m_e c^2) \sigma_T \int N_e dl$ . A rough approximation of the integral is  $f$  times the mean baryon density times the Hubble radius, i.e.  $f n_b c H_0$ . Then for  $kT_e = 10 keV$ ,  $y \sim 4 \times 10^{-5} f$ . The limit on  $y$  from the COBE data is (Fixsen et al. 1996)  $y \lesssim 10^{-5}$  which implies that  $f \lesssim 1/4$ . If  $f \sim 0.001$  as inferred from the local density of SCs, then the presence of hot gas in these SCs is consistent with the upper limit to the spectral distortion of the CMB.

## 7. Conclusions

Evidence is presented in this paper for X-ray emission associated with the plane of the local supercluster (LSC). While this has been suggested previously (Jahoda 1993), we argue that the emission is unlikely to be produced by individual sources but rather is diffuse in nature. This implies that there is a great deal of hot ( $\sim 10 keV$ ), diffuse ( $\sim 2.5 \times 10^{-6} cm^{-3}$ ) gas in the LSC and that the gas may account for the bulk of baryonic matter in the local universe. The presence of such gas would be imprinted on the cosmic microwave background (CMB) as a Sunyaev-Zel'dovich temperature decrement of  $\sim -10 \mu K$ . While the COBE 53 GHz map is consistent with such structure, other systematics preclude the positive identification of this component. Even if superclusters are relatively plentiful in the

universe and hot gas in them is common, the resulting fluctuations in the CMB would be small relative to the those found in the COBE data and, therefore, unlikely to compromise the cosmological implications of those fluctuations.

It should be emphasized that the existence of hot, diffuse gas in the LSC is by no means firmly established. The results presented here constitute only a  $2$  to  $3\sigma$  effect and  $3\sigma$  results have a history of disappearing. Also the source of the X-ray emission may not be diffuse, hot gas; although, we argue that point sources probably do not account for it. None-the-less, the results are tantalizing and are consistent with the density and temperature of gas that might be expected to inhabit the intergalactic medium. It is unlikely that more detailed analyses of the HEAO and COBE data will shed more light on the situation. The signals to noise of these maps are simply not good enough. However, the next generation of X-ray satellites with higher angular resolution, better frequency resolution, and higher sensitivities will likely be able to either confirm or refute the suggestions made in this paper as well as be able to detect diffuse emission in other relatively nearby superclusters. Finally the new CMB satellites scheduled for launch in the next few years (i.e. MAP and PLANCK) should have the angular and frequency resolution required to distinguish an SZ effect in the LSC from intrinsic CMB fluctuations if the level of the effect is that suggested by this paper.

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Fig. 1.— 2–10 keV HEAO I A2 map in Galactic coordinates (Jahoda & Mushotzky 1989). The units are TOT counts/sec (see text).

Fig. 2.— The autocorrelation function (normalized to unity) of Map#2 (see §3.5) corrected for large-scale structure. The dashed curve is that expected for the Gaussian PSF of the map. The solid curve is a fit to the data to account for the tail of the ACF (see text).

Fig. 3.— LSC emission fit to Map#2 for pillbox models lying in the supergalactic plane with centers rotated by angles in steps of  $30^\circ$  from the nominal center of the LSC in Virgo. The error bars are statistical only and are highly correlated.

Fig. 4.— LSC emission fit to Map#2 for pillbox models with central planes offset from the Galaxy. Vertical position is expressed in terms of the thickness of the pillbox. The error bars are statistical only and are highly correlated.

Fig. 5.— LSC emission fit to Map#2 for pillbox models with centers displaced from the Galaxy. Radial position is expressed in units of the supercluster radius. The nominal value is 0.8. Negative values indicate models with centers in the direction opposite Virgo. The error bars are statistical only and are highly correlated.

Fig. 6.— Average 2–10 keV flux of Map#2 binned according to level of emission predicted from the pillbox model. The predicted emission is taken from Table 1 and the map is corrected for all fit large-scale structure except for LSC emission. The error bars are statistical only.

Fig. 7.— The autocorrelation function (normalized to unity) of Map#2. For  $\theta > 10^\circ$  the data is binned in  $13^\circ$  bins to reduce scatter. The solid curve is the ACF for the model including all fit large-scale structure plus the fit of Figure 2 for the small-scale ( $< 10^\circ$ ) structure.

Map#1					Map#2				
$k$	$a_k$	$\sigma_a$	$\sigma_b$	$\sigma_c$	$k$	$a_k$	$\sigma_a$	$\sigma_b$	$\sigma_c$
1	328.17	0.36	1.30	1.49	1	329.06	0.42	1.49	1.73
2	3.38	0.29	1.06	1.18	2	3.16	0.34	1.21	1.37
3	6.38	0.29	0.99	1.06	3	6.26	0.34	1.15	1.30
4	3.23	0.18	0.64	0.70	4	2.25	0.21	0.74	0.84
5	0.10	0.01	0.05	0.05	5	0.06	0.02	0.05	0.06
$\chi^2_\nu$		3.57	0.99	0.99	$\chi^2_\nu$		2.96	1.00	1.00

Table 1: Fit parameters for Maps#1 and #2. The units are  $0.01 \text{ TOT cts/sec}/4.5 \text{ deg}^2 \approx 1.54 \times 10^{-10} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$ . The parameter  $a_1$  corresponds to the intensity of the XRB,  $a_2$  is emission from the LSC,  $a_3$  is detector drift,  $a_4$  is Galactic secant law emission, and  $a_5$  is emission proportional to the Haslam map (in units of  $0.01 \text{ TOT cts/sec}/4.5 \text{ deg}^2/\text{K}$ ).  $\sigma_a$  is the error in the fit for photon counting noise only,  $\sigma_b$  includes fluctuations in the XRB modeled as the dashed curve in Figure 2, and  $\sigma_c$  includes fluctuations modeled as the solid curve of Figure 2.

	$a_1$	$a_2$	$a_3$	$a_4$	$a_5$
$a_1$	1.0	-0.4	-0.1	-0.5	-0.5
$a_2$	-0.4	1.0	0.0	0.2	0.0
$a_3$	-0.1	0.0	1.0	-0.3	0.0
$a_4$	-0.5	0.2	-0.3	1.0	-0.3
$a_5$	-0.5	0.0	0.0	-0.3	1.0

Table 2: Correlation coefficients for the fit parameters for Map#1 in Table 1. The fit parameters,  $a_k$ , are defined as in Table 1. The coefficients for Map#2 are similar.

6.000E+00



0.000E+00

















